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Key Points:

- Snow accumulation shows strong correspondence with snow cover duration across elevations
- The influence of timing and accumulation of snow on start and length of the growing season is more pronounced above 1,500 m than below
- Snow cover duration plays a more significant role than snow accumulation on Alpine start and length of the growing season

Supporting Information:

- Supporting Information S1
- Data Set S1

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Relative Influence of Timing and Accumulation of Snow on Alpine Land Surface Phenology

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Abstract Timing and accumulation of snow are among the most important phenomena influencing land surface phenology in mountainous ecosystems. However, our knowledge on their influence on alpine land surface phenology is still limited, and much remains unclear as to which snow metrics are most relevant for studying this interaction. In this study, we analyzed five snow and phenology metrics, namely, timing (snow cover duration (SCD) and last snow day), accumulation of snow (mean snow water equivalent, SWE_m), and mountain land surface phenology (start of season and length of season) in the Swiss Alps during the period 2003–2014. We examined elevational and regional variations in the relationships between snow and alpine land surface phenology metrics using multiple linear regression and relative weight analyses and subsequently identified the snow metrics that showed strongest associations with variations in alpine land surface phenology of natural vegetation types. We found that the relationships between snow and phenology metrics were pronounced in high-elevational regions and alpine natural grassland and sparsely vegetated areas. Start of season was influenced primarily by SCD, secondarily by SWE_m, while length of season was equally affected by SCD and SWE_m across different elevational bands. We conclude that SCD plays the most significant role compared to other snow metrics. Future variations of snow cover and accumulation are likely to influence alpine ecosystems, for instance, their species composition due to changes in the potential growing season. Also, their spatial distribution may change as a response to the new environmental conditions if these prove persistent.

1. Introduction

Global climate is changing more rapidly in alpine and arctic regions than in other areas, and the average temperature in alpine areas is expected to continue to rise faster than the average global increase (Intergovernmental Panel on Climate Change (IPCC), 2007, 2014). Changes in mountainous vegetation phenology are considered an important and observable trace of mountainous ecosystem response to these climatic changes (Jonas et al., 2008; Menzel et al., 2006), as well as a key determinant of coupled water and energy exchange (White et al., 2009), land surface carbon fluxes (Barrio et al., 2013; Richardson et al., 2010), and species distributions (Chuine & Beaubien, 2001). As a climate driver, snow is one of the most important controlling factors in mountainous ecosystems (Cornelius et al., 2013; Wipf et al., 2009). It shields harsh winds and provides frost protection in winter (Chen, An, et al., 2015; Desai et al., 2016; Groffman et al., 2006; Wahren, et al., 2005; Wipf et al., 2006) and nutrient mobilization and water supply in spring (Keller & Körner, 2003). Variations in timing and accumulation of snow have been reported to significantly influence vegetation phenology, as well as the energy balance (Euskirchen et al., 2007), water cycling (Barnett et al., 2005; Rawlins et al., 2006), and soil carbon cycling (Dorrepaal et al., 2003; Monson et al., 2006). For these reasons, it is critical to understand the response of alpine land surface phenology to the variation of the timing and accumulation of snow, which can change ecological interactions and thereby reshape alpine ecosystems.

Many studies have documented that the timing and accumulation of snow influence the start and length of mountainous land surface phenology (Chen, Liang, et al., 2015; Dunne, 2003; Jonas et al., 2008; Paudel & Andersen, 2013; Trujillo et al., 2012; Yu et al., 2013). For instance, a larger snowpack and longer snow cover duration can result in later snowmelt and timing of phenological events (Cooper et al., 2011; Inouye, 2008). In contrast, shorter snow cover duration and earlier snowmelt often advance plant development (Chen et al., 2011; Dunne, 2003; Hu et al., 2010; Wipf et al., 2009; Wipf & Rixen, 2010). Moreover, both the timing and accumulation of snow (Beniston et al., 2003; Hüsler et al., 2014; Trujillo et al., 2012) and phenological events (Benadi et al., 2014; Cornelius et al., 2013; Defila & Clot, 2005; Lambert et al., 2010; Schuster et al.,

2014) have been reported to change with elevation. For a long time, the timing and accumulation of snow have been referenced as important drivers of mountainous ecosystems across topographic gradients (Wipf & Rixen, 2010). Several studies have documented that the impacts of snow metrics on vegetation growth and land surface phenology varied with elevation and geographical region (Huelber et al., 2006; Keller et al., 2005; Paudel & Andersen, 2013; Trujillo et al., 2012; Xie et al., 2017). More specifically, above 2,000 m asl in the European Alps, the snow cover duration was reported to be positively correlated with the start of the growing season but negatively correlated with the length of the growing season. Besides, the last snow day was found to be moderately correlated with the start and length of the growing season (Xie et al., 2017). In high-elevation drier regions in Nepal Trans Himalaya, the last snow day was also observed to be highly correlated with the start of the growing season (Paudel & Andersen, 2013) and in northern China, the start of the growing season was reported to be sensitive to snow depth change for most of the alpine and subalpine vegetation (Yu et al., 2013). In the Sierra Nevada region, maximum snow accumulation and the date of snow disappearance were reported to explain variability in vegetation greenness between 2,000 and 2,600 m asl because snow melt eases water limitation (Trujillo et al., 2012). Nevertheless, there is a lack of detailed studies comparing the impact of multiple snow metrics on land surface phenology of snow-dominated mountainous regions. Furthermore, in particular the relative importance and weight of snow timing and snow accumulation to the alpine phenology is not fully understood. This study is based on a large amount of available data spanning the entire Swiss Alps to investigate the characteristics, magnitude, and elevation dependency of these relationships.

Snow metrics are known to covary under certain conditions. For instance, the date of snow disappearance may be correlated with the maximum snowpack accumulation (Trujillo et al., 2012). Similarly, in combination with spring temperatures, the winter snow depth codetermines the time of snow melting (Richardson et al., 2013). Moreover, snow cover duration is closely linked to both the start day and melt day of snow cover in high-elevational regions with continuous snow cover (Hüsler et al., 2014). However, across elevation, the characteristic and magnitude of the correlation between snow timing and snow accumulation still need detailed understanding. Furthermore, while (i) the snow cover duration is highly correlated with the start and the length of a phenological cycle and (ii) the last snow day is moderately correlated with the start of the growing season in high-elevational regions, the elevation-dependent amount of snow accumulation and its influence on mountainous land surface phenology require further investigation. In snow sensitive regions with weak or no interdependence between timing and accumulation of snow, the relative importance of these parameters remains to be assessed to find most relevant metrics for studying snow-vegetation dynamics.

As a consequence, investigations of relationship between snow and phenology metrics may facilitate the understanding of the mechanisms of vegetation response to snow cover and accumulation in mountainous ecosystems, as well as the magnitude of the relative importance between these snow metrics to land surface phenology. In this study, we focused on snow timing (SCD and last snow day (LSD)), snow accumulation (SWE_m), and alpine land surface phenology (start of season, SOS; length of season, LOS) for the period 2003–2014 in the Swiss Alps. We aimed to (i) test the variation of snow accumulation and its correspondence with snow timing across elevation, (ii) investigate the characteristic and magnitude of the influence of snow accumulation and snow timing on land surface phenology, and (iii) identify the snow metric that has the strongest effect on land surface phenology for different elevations and regions.

2. Material and Methods

2.1. Study Area

Located in the central European Alps, the Swiss Alps (6.8°E–10.5°E, 45.8°N–47.4°N) encompass an area of 25,194 km^2 (Figure 1). They were selected for our analysis given their typical mountainous character with complicated topography (Jonas et al., 2008; McVicar et al., 2010; Scherrer et al., 2004), as well as long-term changes of snow attributed to climate changes (Beniston et al., 2003; Marty et al., 2017; OcCC-Consortium, 2007). We separated the study region into the northern Swiss Alps (NSA; 10,867 km^2, 43.1% of total area), the eastern Swiss Alps (ESA; 5,825 km^2, 23.1%), the southern Swiss Alps (SSA; 3,667 km^2, 14.6%), and the western Swiss Alps (WSA; 4,834 km^2, 19.2%) according to the subdivision of biogeographical regions (Gonseth et al., 2001). NSA, WSA, and ESA are subject to temperate westerly and oceanic features of

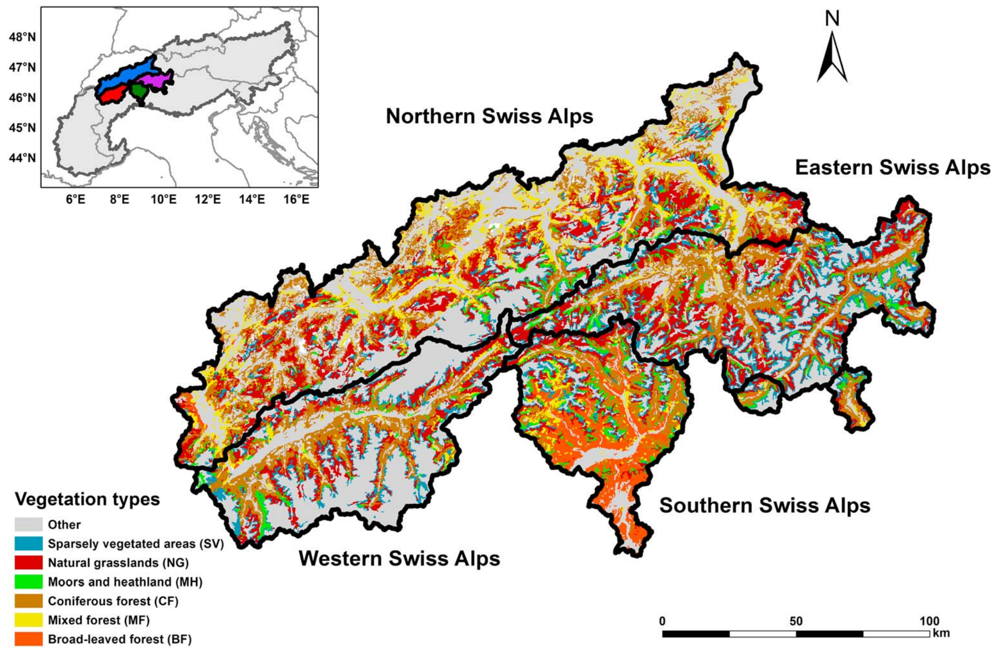

Figure 1. Location and natural vegetation types of the Swiss Alps (separated as northern Swiss Alps, eastern Swiss Alps, southern Swiss Alps, and western Swiss Alps).

climate variability, while SSA experiences Mediterranean subtropical and oceanic features of climate variability (Auer et al., 2007). At particular times, the NSA often show different climatic conditions compared to the SSA (Laternser & Schneebeli, 2003). The climate of the four subregions has differed in past decades and is expected to differ in the projected future (Rammig et al., 2010). The subregions are assumed to reflect different ecological and climatological regimes. We focused on six natural vegetation (NV) types (Figure 1), excluding the areas that experienced land cover change between 2000 and 2012 (i.e., 2.5% of NV in 2000), based on the CORINE Land Cover 2000 and 2012 seamless vector data (http://land.copernicus.eu/, accessed May 2017). NV in our statistical analysis covers 60.0% of the study area and includes broad-leaved forest (BF, 6.8% of NV), mixed forest (MF, 8.8% of NV), coniferous forest (CF, 35.7% of NV), moors and heathland (MH, 7.1% of NV), natural grasslands (NG, 32.0% of NV), and sparsely vegetated areas (SV, 10.1% of NV). NV is found at elevations up to 3,000 m asl, bordering with the alpine-nival ecotone (Gottfried et al., 2011).

2.2. Snow Metrics

In this study, we defined the SCD as the total number of snow-covered days in each water year (WY, running from 1 October to 30 September of the following year) (Hüsler et al., 2014; Xie et al., 2017), the LSD as the last snow-covered date in each WY, and the snow accumulation, that is, SWE_m, as the mean value of snow water equivalent (SWE) of the corresponding SCD in each WY. LSD is expressed in a day of the (calendar) year and SCD is expressed in days of each WY (days). The unit of SWE is millimeter (mm). These snow metrics can provide information about the spatiotemporal variation of timing and accumulation of snow characteristics in the Swiss Alps for the period 2002–2014.

To derive these snow metrics, we employed snow cover maps (SCM) at 250 m/daily resolution (Notarnicola et al., 2013a, 2013b) and a SWE grid at 1 km/daily resolution (Jonas et al., 2009; Magnusson et al., 2014). SCM were obtained from Terra Moderate Resolution Imaging Spectroradiometer images with a tailored topographic correction and improved ground resolution of 250 m in order to take into account the specific characteristics of mountainous areas (Notarnicola et al., 2013a, 2013b). The daily SWE data, being generated on the basis of 298 observational snow monitoring sites in Switzerland using a distributed snow hydrological model (Griessinger et al., 2016; Magnusson et al., 2014), were assessed using validation points following the methods of Foppa et al. (2007) and further elaborated by Magnusson et al. (2014). SWE grids were resampled to 250 m resolution using the Nearest Neighbor method in order to match the SCM.

The calculation of SCD and LSD, using the method described in Xie et al. (2017), was based on the daily availability of SCM. The LSD can provide useful information about the melting process, given that multiple late season transient snow patterns and snowfall occur during snowmelt seasons (Crawford et al., 2013; Hüsler et al., 2014) across elevations. Moreover, a pixel of the SWE grid is involved in the calculation of SWE_m only if the corresponding SCM pixel is identified as snow cover (Figure S1 in the supporting information) using the method described in Xie et al. (2017). The detailed calculation of SWE_m is presented in Text S1.

2.3. Phenology Metrics

We used remote sensing data sets to assess land surface phenology metrics, largely because field-based surveys are mostly restricted to species level information in mountainous regions (Chen, An, et al., 2015; Pellerin et al., 2012) and have limited spatial coverage (Fisher et al., 2006; Studer et al., 2007). Satellite remote sensing supports monitoring and characterizing land surface phenology of vegetated areas, as well as responses to changing climate at landscape level and across ecological scales (Paudel & Andersen, 2013; Trujillo et al., 2012; Yu et al., 2013).

Normalized Difference Vegetation Index (NDVI) is one of the most widely used indices for monitoring land surface phenological events at various scales (Cleland et al., 2007; Fisher et al., 2006; Garonna et al., 2014, 2016). NASA Moderate Resolution Imaging Spectroradiometer/Terra NDVI products (MOD13Q1-collection 5) were used to derive yearly phenology metrics for SOS and LOS on a pixel-by-pixel basis. The available 276 MOD13Q1 images were of 250 m/16 day resolution, spanning from 2003 to 2014, with corresponding quality and day-of-observation information data.

To derive SOS from the annual NDVI time series, we selected the day when NDVI reached half its annual range. This relative threshold method—called $\text{Midpoint}_{\text{pixel}}$—is based on the comprehensive intercomparison of SOS metrics by White et al. (2009). The end of season is then defined as the day on which NDVI reaches the midpoint again in the calendar year, and the LOS is simply the number of days between SOS and end of season. For the calculation of each annual SOS and LOS using MOD13Q1 images, the method described by Xie et al. (2017) was applied in NV areas. SOS is always expressed in day of (calendar) year and LOS in days.

2.4. Statistical Analysis

Topographic information of the study area at a 1 arc sec scale (~30 m) obtained from the European Environment Agency (http://www.eea.europa.eu/, accessed May 2017) was used to generate a 250 m scale digital elevation model (DEM). The maps of snow and phenology metrics were transformed to zone 32 of the Universal Transverse Mercator projection and resampled to a 250 m grid for statistical analysis. Then, a Pearson correlation was employed to test the correlation between snow metrics (i.e., SCD&LSD, SCD&SWE_m, and LSD&SWE_m) on an interannual timescale based at pixel level. Linear least squares regression was used to analyze the interannual trend (significance defined as $p < 0.05$) over the study period for each pixel and the elevation-dependent responses (significance defined as $p < 0.001$) of 12 year averaged values for each snow and phenology metric. Partial Spearman's correlation, which can remove the dependency effects from other parameters, was used to estimate the correlation (based on a two-tailed significance test and $p < 0.05$) between SWE_m and phenology metrics for each pixel. Multiple linear regression was employed to investigate the characteristic and magnitude of the relationships (significant model was selected with $p < 0.05$) between snow and phenology metrics. This method was applied to identify the key snow metrics (excluding the pixels with significant Pearson correlation between snow metrics) with direct influence on phenology metrics (significance defined as $p < 0.05$ for each predictor in each model) based on pixel level. The slopes of the multiple linear regressions between snow and phenology metrics were calculated to determine variation in the strength of the relationships between snow and phenology metrics.

Accordingly, the generalized model is expressed as follows:

$$y = f(\text{SCD}, \text{LSD}, \text{SWE}_\text{m}), \text{ where } y \text{ is SOS or LOS} \tag{1}$$

The R^2 of the multiple linear regressions (1) quantitatively explain the relationship between snow and phenology metrics. Johnson (2000) defined relative weight as the contributing proportion of each predictor to R^2, considering both its contribution combined with other variables and its unique contribution. We used relative weight (% of R^2) analysis to assess the relative importance of snow metrics based on R^2, as well as to identify the snow metric with the strongest effect on alpine phenology.

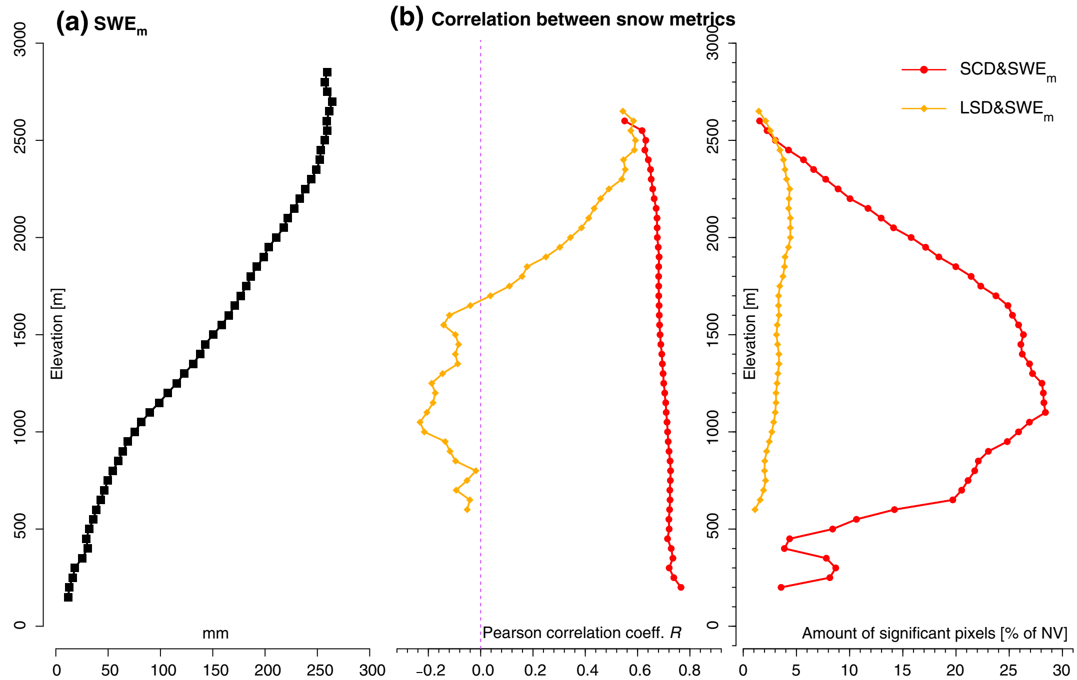

Figure 2. Elevational variation in mean mean snow water equivalent (SWE_m) for the period 2003–2014 (a) and mean Pearson correlation coefficients (a) between snow metrics (i.e., snow cover duration (SCD) and SWE_m and last snow day (LSD) and SWE_m) and the corresponding amount of significant pixels [% of total] (b) across the entire Swiss Alps. The dashed line represents a mean correlation coefficient of 0.

The 250 m grids of statistical results were intersected with the 250 m subregions and NV maps. The elevation-dependent analyses consisted of selecting distinct zones within a 100 m band with a 50 m elevational resolution (between 200 and 3,000 m asl, corresponding to the range of elevational distribution of NV types), based on the DEM across the study area. The statistics between snow and phenology metrics were analyzed along elevation gradients and between the four subregions. The corresponding values for each band contain the mean statistically significant results, such as the mean correlation coefficient and mean regression slopes. Bands with (i) mean SCD larger than 360 days, (ii) mean SCD lower than 10 days, and (iii) the proportion of pixels in statistical significance less than 1% masked out in the elevational analysis. Image data processing was performed using ArcGIS (v10.4.1, ESRI, USA), ENVI/IDL (v5.1, the EXELIS Inc., McLean, VA, USA), and statistical analysis was performed using the R (v3.2.3) program environment.

3. Results

3.1. Variation of SWE_m and Correlations Between Snow Metrics With Elevations

In the areas of NV types, SWE_m varies with elevations (Figure 2a) and increases by 5.46 (±0.10) mm/50 m between 200 and 3,000 m asl. Above 1,500 m asl, where grasslands dominate (Figure S2a), SWE_m amounts to more than 150 mm, while SWE_m is less than 150 mm at lower elevations. The mean SWE_m in WSA and ESA are larger than in NSA and SSA, with the mean SWE_m in NSA being larger than in SSA.

SWE_m showed a strong significant positive correlation with SCD (with mean $R = 0.69$), and the mean correlation coefficients slightly decreased with elevation (Figure 2b). The corresponding amount of pixels with significant correlation accounted for 26.5% of NV and reached a maximum between 1,000 and 1,500 m asl. However, SWE_m presented a less significant correlation with LSD across elevation (Figure 2). In addition, the significant correlations between SWE_m and LSD above 2,000 m asl (with mean $R = 0.53$) were stronger than those in other elevations but were only present in a few pixels (<5% of NV). The spatial patterns of Pearson correlation coefficients between snow metrics (i.e., SCD&LSD, SCD&SWE_m, and LSD&SWE_m) are presented in Figure S3.

Over the 12 investigated years, less than 5% of total pixels showed a significant temporal trend ($p < 0.05$) in both snow (i.e., SCD, LSD and SWE_m) and phenology (i.e., SOS and LOS) metrics across the entire research area

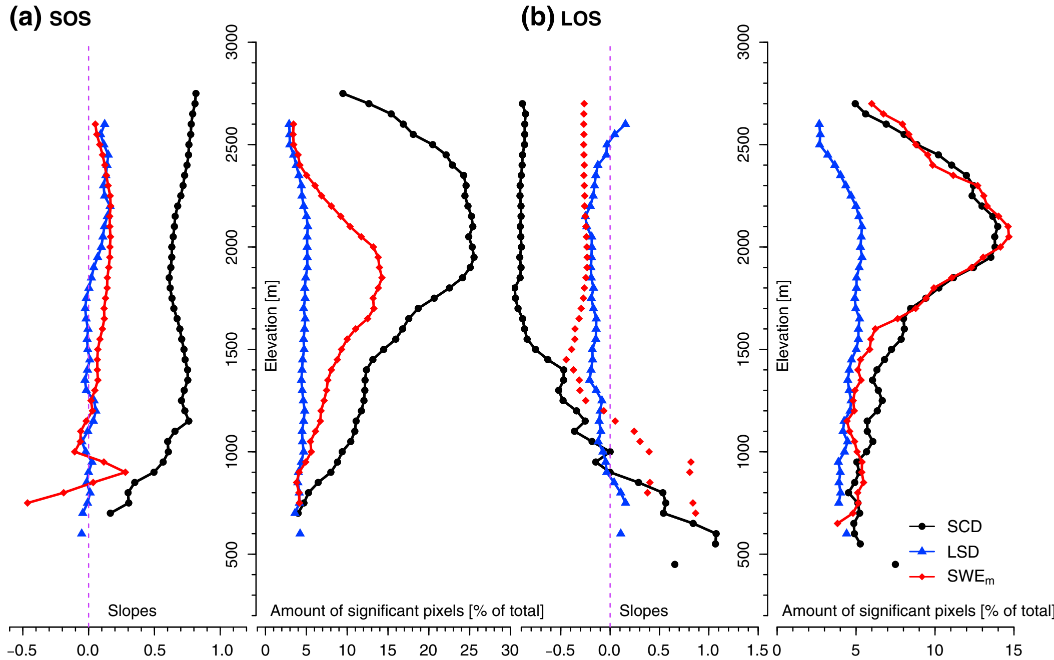

Figure 3. Elevational variation in mean multiple linear regression slopes (a) between snow and phenology metrics (i.e., snow cover duration (SCD) and start of season (SOS), last snow day (LSD) and SOS, mean snow water equivalent (SWE$_m$) and SOS (d/mm) (a); SCD and length of season (LOS), LSD and LOS, SWE$_m$ and LOS (d/mm) (b)) and the corresponding amount of significant pixels [% of total] (b) of each snow metric for the Swiss Alps. A total of 65.7% of all natural vegetation pixels were employed in this analysis. Dashed lines represent a mean regression fit of 0.

by estimation of linear least squares regression. In addition, both snow and phenology metrics changed with elevation (Figure S2). Linear least squares regression (significant with $p < 0.001$) results showed that both snow and phenology metrics responded to the change of elevation across the entire study area (Text S2). The spatial patterns of elevational gradients, SOS, LOS, SCD, LSD, and SWE$_m$ are presented in Figure S4.

3.2. Multiple Linear Regressions Between Snow and Phenology Metrics Depending on Elevations and Subregions

As an overview of the correlation between SWE$_m$ and phenology parameters, partial Spearman's correlation values have been computed between SWE$_m$ and SOS and between SWE$_m$ and LOS, as well as the corresponding amount of significant pixels depending on elevation. The mean R between SWE$_m$ and SOS was larger than 0.60 between 1,500 and 2,000 m asl, and the corresponding significant pixels amounted to 15–20%. A negative correlation between SWE$_m$ and LOS (mean $R < -0.60$) was found above 1,500 m asl, and the corresponding significant pixels amounted to 15–20%, as well (see Figures S5 and S6).

In the following multiple linear regression analysis between snow metrics (i.e., SCD and LSD, SCD and SWE$_m$, and LSD and SWE$_m$) a total of 34.3% NV pixels (see Figure S3) with significant Pearson correlation ($p < 0.05$) was excluded to avoid duplicate information. The mean slopes of the multiple linear regression between snow and phenology metrics with elevation are shown in Figure 3. SCD showed a positive relationship for SOS, and with the largest amount of corresponding significant pixels, compared to LSD and SWE$_m$, with elevation (Figure 3a). The slopes of SOS with SCD showed no apparent change (between 0.6 and 0.8) above 1,500 m asl in regions which were dominated by grassland (i.e., SV, NG, and MH), with corresponding pixels reaching a maximum (>25%) between 1,900 and 2,400 m asl. In comparison, the LSD showed a much weaker significant relationship for SOS than SCD for SOS and had a much smaller amount of significant pixels (<7%) across elevation. The relationship of SOS with SWE$_m$ was positive above 1,500 m asl and reached a maximum (mean slopes between 0.18 and 0.20 d/mm) between 1,800 and 2,400 m asl. In contrast, a few pixels with significance had negative slopes below 1,500 m asl in regions which were dominated by forest (i.e., CF, MF, and BF).

Above 1,500 m asl, the relationships of LOS with SCD (mean slopes >-0.70) and with SWE$_m$ (mean slopes around -0.20 d/mm) showed no apparent variation with elevation, and presented an equal maximum of

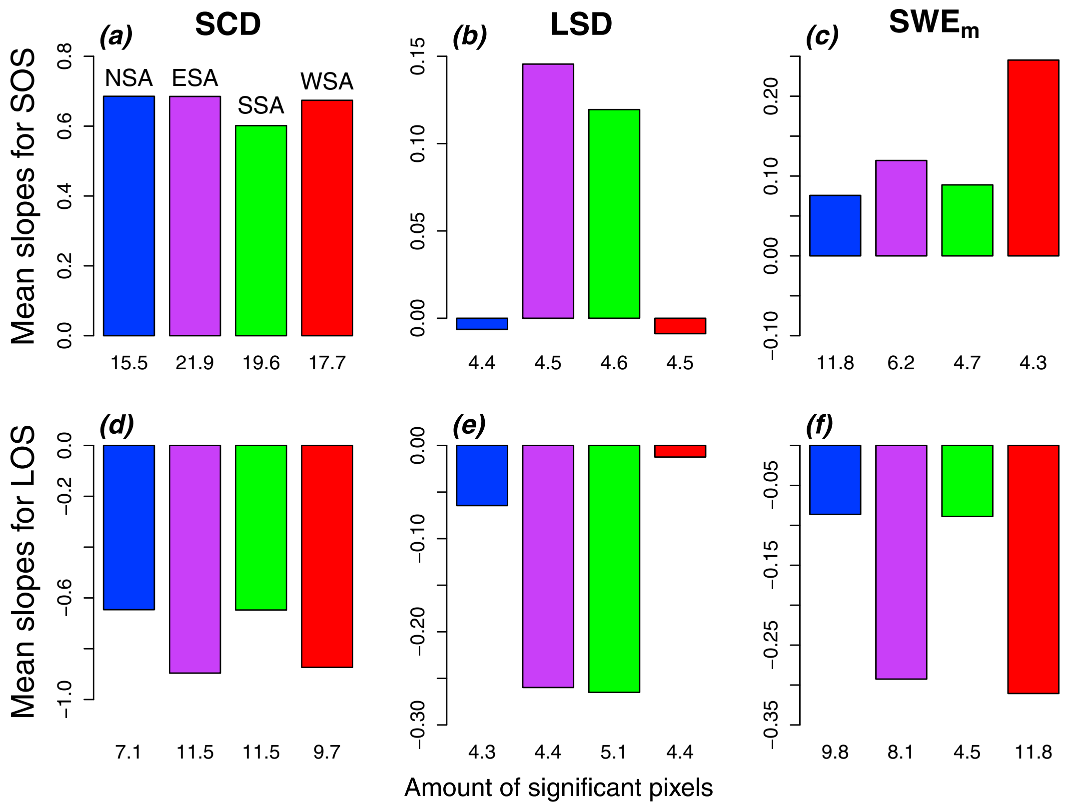

Figure 4. Mean multiple linear regression slopes between snow and land surface phenology metrics (i.e., snow cover duration (SCD) and start of season (SOS) (a), last snow day (LSD) and SOS (b), mean snow water equivalent (SWE_m) and SOS (d/mm) (c), SCD and length of season (LOS) (d), LSD and LOS (e), SWE_m and LOS (d/mm) (f)) and the corresponding amount of pixels with a significant regression [% of total] for each snow metric for the four subregions (northern Swiss Alps (NSA), eastern Swiss Alps (ESA), southern Swiss Alps (SSA), and western Swiss Alps (WSA)). A total of 65.7% of all natural vegetation pixels were employed in this analysis.

corresponding significant pixels between 2,000 and 2,200 m asl (Figure 3b). The relationships of LOS with SCD, with LSD and with SWE_m varied from positive to negative between 900 and 1,200 m asl with elevation. In contrast to the results of SOS, the positive relationships of LOS with SCD, LSD, and SWE_m were mainly below 1,500 m asl with fewer corresponding significant pixels (<7%). SOS and LOS in SV, NG, and MH showed stronger and broader impacts from snow metrics than those in CF, MF, and BF. (Figures S7–S9).

The relationship of SOS with SCD (mean slopes > 0.60) showed slight differences between the four subregions (Figure 4a). Mean slightly positive slopes of the relationship of SOS with LSD were only found in the ESA and the SSA and for a smaller portion of corresponding significant pixels (Figure 4b). The mean negative relationship of SOS with SWE_m in SSA is in contrast with the positive relationships in the other subregions (Figure 4c). The relationships of LOS with SCD in ESA and the WSA (mean slopes < -0.90) were stronger than those in the NSA and SSA (mean slope < -0.60) (Figure 4d). Mean slightly negative slopes of the relationship of LOS with LSD were only found in ESA and SSA and with a smaller portion of corresponding significant pixels (Figure 4e). The relationships of LOS with SWE_m in ESA and WSA (mean slope < -0.25 d/mm) showed much stronger negative slopes than those in NSA and SSA (mean slopes < -0.05 d/mm) (Figure 4f). The spatial patterns of multiple linear regression relationships between snow and phenology metrics (i.e., SCD and SOS, LSD and SOS, SWE_m and SOS, SCD and LOS, LSD and LOS, and SWE_m and LOS) are presented in Figure S10.

3.3. Relative Weights of Snow on Phenology Metrics Depending on Elevations and Subregions

Figure 5 shows the relative weight (% of R^2) of snow metrics on phenology metrics with elevation. The mean R^2 ($p < 0.05$) of the multiple linear regressions between snow and phenology metrics ranged between 0.70 and 0.75 across elevation (Figure S11). The relative weight of SCD on SOS increased from 40% to 70% and was

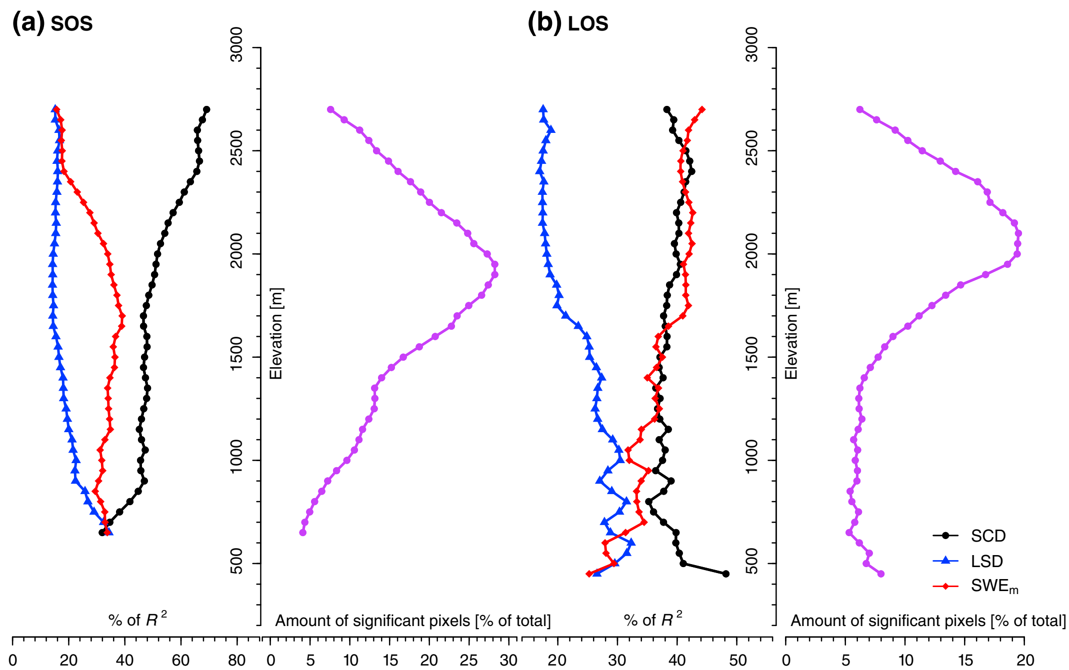

Figure 5. Elevational variation in mean relative weight [% of R^2] (a) of snow metrics (i.e., snow cover duration (SCD), last snow day (LSD), and mean snow water equivalent (SWE_m)) on start of season (SOS) (a) and length of season (LOS) (b), and corresponding amount of significant pixels [% of total] (b) for the Swiss Alps. A total of 65.7% of all NV pixels was employed in this analysis.

the highest across elevation (Figure 5a). The corresponding percentage of significant pixels of the multiple linear regression models increased with elevation until reaching a maximum at 2,000 m asl with 23%, and decreased again afterward. Above 1,500 m asl, SCD showed the largest relative weight (>50%), increasing with elevation. SWE_m had less than 30% relative weight across elevation. Below 1,500 m asl, SCD was still the dominating metric but with less relative weight than above 1,500 m asl. Meanwhile, SWE_m had about 35% relative weight.

SCD and SWE_m had similar relative weights on LOS across elevation (Figure 5b). The corresponding amount of significant pixels for R^2 was higher above 1,500 m asl and reached a maximum at 2,200 m asl. The relative weight values were also higher above 1,500 m asl than below. LSD showed the least relative weight on both SOS and LOS across elevations. The relative importance (% of R^2) of SCD, LSD, and SWE_m to SOS and to LOS, obtained over the entire study area for six vegetation types (BF, CF, MF, NG, MH, and SV), are presented in Figures S12–S14.

The mean R^2 of the multiple linear regressions between snow and phenology metrics showed no difference between the six NV types (Figures S12d and S12h), as well as the four subregions (Figures S15 and S16). More precisely, the amount of significant pixels in R^2 of snow metrics to SOS is almost equal between the four subregions (18.8% in NSA, 18.0% in ESA, 17.5% in SSA, and 17.9% in WSA), whereas for LOS, the amount is slightly lower in NSA (10.5%) than in the other subregions (12.9% in ESA, 11.2% in SSA, and 14.5% in WSA) (Figure S16).

Figure 6 shows that the relative weights (% of R^2) of SCD on SOS and LOS are slightly higher in ESA and SSA than in NSA and WSA. In contrast, the relative weights of SWE_m on SOS and LOS are higher in NSA and WSA than in ESA and SSA (Figures 6c and 6f). The relative weights of LSD on SOS and LOS, however, only showed slight differences with a mean value around 20% (Figures 6b and 6e). The spatial patterns of the relative weights of SCD, LSD, and SWE_m on SOS and on LOS for the entire study area are presented in Figure S17.

4. Discussion

4.1. Variation in SWE_m and Correlations Between Snow Metrics With Elevation

Our results in section 3.1 and Figure 2 present a significant positive correlation between SCD and SWE_m across elevations in the Swiss Alps. This finding is in agreement with previous studies that showed snow

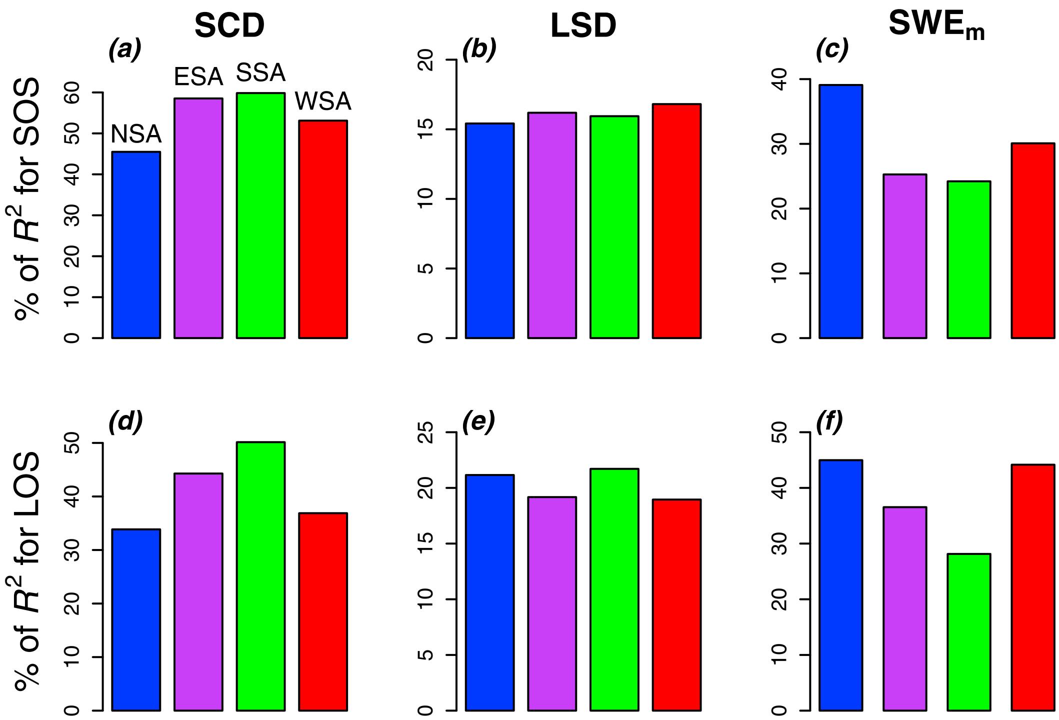

Figure 6. Mean relative weight [% of R^2] of snow metrics (i.e., snow cover duration (SCD), last snow day (LSD), and mean snow water equivalent (SWE_m) on start of season (SOS) (a–c) and on length of season (LOS) (d–f)) for the four subregions (northern Swiss Alps (NSA), eastern Swiss Alps (ESA), southern Swiss Alps (SSA), and western Swiss Alps (WSA)). A total of 65.7% of all NV pixels was employed in this analysis.

cover being correlated with snow accumulation metrics such as snow depth and SWE (Metsämäki et al., 2012; Yu et al., 2013). However, the lack of a significant correlation between SCD and LSD, as well as between LSD and SWE_m (Figure 2), is in contrast to a study performed in the Sierra Nevada Mountains, USA (Trujillo et al., 2012), where a strong correlation of LSD with maximum SWE is reported, albeit under different climatic conditions than in our study area. This may be due to the fact that SCD is closely linked to LSD only in alpine regions with continuous snow cover (Bormann et al., 2012; Dedieu et al., 2014; Hüsler et al., 2014). LSD is different from the snow melting day because of the existence of multiple late season transient snow patterns and snowfall during snowmelt seasons in the study area (Hüsler et al., 2014). Therefore, our findings may further indicate that SCD and SWE_m have no significant correlation with the multiple late season transient snow patterns and snowfall during snowmelt seasons in the study area.

The elevational variation of SOS and LOS (Text S2 and Figures S2b and S2c) confirm the dependency of both SOS and LOS on elevation in mountainous areas (Cornelius et al., 2013; Gottfried et al., 2012; Hwang et al., 2011; Richardson et al., 2006). These results are in line with previous reports presenting the variation in the snow timing and accumulation with elevation in mountainous regions (Bormann et al., 2012; Hüsler et al., 2014).

In this study, we found no significant trend in both snow (i.e., SCD, LSD, and SWE_m) and phenology (i.e., SOS and LOS) metrics during 2003–2014 (Text S2). This was also the case for snow metrics in previous studies over the period 1990–2011 (Hüsler et al., 2014; Marty, 2008). However, our finding is in disagreement with Defila and Clot (2005) who reported significant trends of phenology metrics over the study region in recent decades, although they considered much longer time extents (50 years). This inconsistency may be due to differences in study periods, since the strength and direction of a trend can strongly depend on time periods considered (Marty et al., 2017).

4.2. Influence of Snow on Phenology Metrics Depending on Elevations and Subregions

At elevations above 1,500 m asl, dominated by SV and NG, we found that snow metrics (i.e., SCD, LSD, and SWE_m) had stronger relationships with SOS and LOS than below 1,500 m asl, where forests are prevalent (see Figures 3 and S7–S9). These results correspond well to the fact that both timing and accumulation of snow have a great effect on determining phenology in high-elevation regions (Huelber et al., 2006; Hülber et al., 2011; Wipf et al., 2009). Furthermore, our results are in agreement with the conclusion that the vegetative season can be reduced by longer lasting snow cover (Björk & Molau, 2007; Cooper et al., 2011), and that a deep snowpack invariably leads to delaying the plant growing season (Borner et al., 2008; Löffler, 2005) (Figure 3).

Our findings indicate that the SWE_m impacts vegetation growth in an alpine ecosystem (Figures 4c and 4f). This is in line with experimental studies of Dunne (2003), which reported on shallower snowpacks leading to an earlier SOS for most of the subalpine species in Gunnison County, Colorado (USA). Our findings are also in agreement with Trujillo et al. (2012), who report that maximum SWE explained 50% of the significant variability in maximum NDVI between 1,900 and 2,600 m asl in the Sierra Nevada region during the period 1982–2006. Furthermore, the negative relationship between LOS and SWE_m (Figures 3b and S7d–S7f) may support the fact that increased snow thickness often results in a short-term ecosystem process (Hejcman et al., 2006; Morgner et al., 2010). More specifically, the relationships between SWE_m and phenology (i.e., SOS and LOS) metrics above 1,500 m asl may be due to the fact that a deep snowpack always delays and reduces plant development, thus shortening the growing season (Borner et al., 2008; Inouye, 2008). In addition, snow metrics may influence LOS through their effect on SOS (White et al., 2009) and greenness (Trujillo et al., 2012). The latter can be attributed to the effect that winter snow has an effect on soil water reserves, such as keeping soils moist through the growing season (Hiller et al., 2005; Richardson et al., 2013; Trujillo et al., 2012). However, our results indicate that both SOS and LOS showed no significant responses to LSD across elevation (Figure 3) and subregions (Figures 4b and 4e). This is neither in line with Trujillo et al. (2012), where the LSD explained significant change in vegetation greenness in the Sierra Nevada region, nor with Paudel and Andersen (2013), where the LSD was highly correlated with the start of the growing season in high-elevational drier regions of Nepal Trans Himalaya. These differences may be due to the fact that the climate and other environmental factors in these two regions are different from the Swiss Alps. Specifically, our findings at high elevations corroborate the different relationships of vegetation with snow accumulation and snow cover found between alpine vegetation zones, topography, and climate conditions in the Tibetan Plateau (Wang, Wang, et al., 2017; Wang, Xiao, et al., 2017).

At elevations below 1,500 m asl, which are dominated by forests (coniferous, mixed and broad-leaved forest, i.e., CF, MF, and BF) and where the accuracy of our snow cover data is lower than for grassland and pasture areas (Notarnicola et al., 2013a, 2013b), the responses of SOS and LOS to snow metrics are less pronounced than above 1,500 m asl (Figure 3). This finding comes close to those of previous studies where the effect of snow depth on the start of the growing season of grasslands and shrubs was found to be stronger than that of forests (Yu et al., 2013), and where the influence of winter snow depth variation on spring and summer temperate vegetation growth was primarily dependent on vegetation type (Peng et al., 2010). This may be because atmospheric temperatures are more tightly coupled to trees in forests than to other vegetation types (Körner & Paulsen, 2004). The main influence of snow on taller vegetation (such as forest) growth is through its frost protection (Thompson et al., 2015). Furthermore, the smaller amount of pixels with a significant relationship between snow and phenology metrics in low elevation forest may be due to the fact that the vegetation growing period depends on other factors such as temperature and sunshine duration (Dunne, 2003; Rixen et al., 2010).

The magnitude and character of the responses of SOS and LOS to snow metrics differed between subregions (Figure 4). The responses of SOS and LOS to snow metrics were more pronounced in the WSA and the ESA (regions with higher mean elevations) than in the NSA and the SSA (that have lower mean elevations) (Figures 4 and S10). These differences may be due to the fact that mountainous plants are affected by snow which also varies with elevation (Cornelius et al., 2013). However, the relationships between snow and phenology metrics also showed spatial variation with elevation when vegetation type and subregion were the same (Figures 3 and S8–S10). In a word, we found that in the Swiss Alps, the influence of snow metrics on SOS and LOS is different between different vegetation types and subregions, and the differences are more pronounced between elevations than between vegetation types and subregions.

Snow metrics mainly presented positive relationships with SOS across elevations (Figure 3), whereas the relationship between snow metrics and LOS changed from negative to positive for elevations below 1,200 m asl (Figure 3). This elevation threshold may be associated with ecological adaptations of the forest relating to water/nutrient requirements and air temperature (Bergeron et al., 2007; Dunn et al., 2007). This finding comes close to the influence of snow accumulation on the start of the growing season, which changed from delay to advance with increasing snow depth in Yu et al. (2013). Therefore, the role of timing and accumulation of snow in mountainous ecosystems might also change with elevation. Specifically, longer SCD and more SWE_m advance the SOS and prolong the LOS at low elevation (<1,000 m asl) (Figures 3 and S8 and S9). This may be due to the fact that the climate at low elevations is warmer than that at high elevations, and snowfall can melt to water quickly. Therefore, longer SCD and more snow accumulation may provide increasing soil moisture and nutrient mobilization, which could be beneficial to the forest growth (Bergeron et al., 2007; Dunn et al., 2007; Walker et al., 1999).

4.3. Relative Influence of Snow on Phenology Metrics Depending on Elevations and Subregions

Our results present different effects of SCD and SWE_m on the interannual variation of SOS and LOS (Figures 5 and S12). These effects appeared to vary with elevation (Figure 5) and between subregions (Figure 6). SCD and SWE_m had more influence on SOS and LOS than LSD across elevations (Figure 5). Indeed, it is important to note that considering possible multiple late season transient snowfall events, LSD did not represent the last date of the continuous winter snow-covered period in our study. LSD may be meaningful in regions with a certain number of days of consecutive snow meltout (Hüsler et al., 2014). Our results showed insignificant influence of LSD on alpine land surface phenology. Furthermore, both SCD and SWE_m explained more interannual variation of SOS than of LOS (Figures 5 and S17a, S17c, S17d, and S17f). These differences might be caused by the fact that duration and depth of snow cover can strongly influence the soil temperature and moisture content in the vegetation growing season, particularly in the early stages (Cooper et al., 2011; Hiller et al., 2005; Löffler, 2005).

In this respect, we found first SOS to be influenced primarily by SCD and second by SWE_m across elevations (Figure 5a). In general, both the snowmelt timing and snow depth have important effects on plant phenology and growth, but the snowmelt timing has stronger implications than snow depth (Wipf et al., 2009). Shorter duration of snow cover is mainly caused by earlier melt of snow cover in spring (Laternser & Schneebeli, 2003). Moreover, the timing and growth of phenological events is highly correlated to the date of snowmelt (Julitta et al., 2014; Rammig et al., 2010; Steltzer et al., 2009). A delayed snowmelt can compress the length of growing seasons and thus may decrease vegetation productivity (Morgner et al., 2010; Wipf & Rixen, 2010). Thus, these arguments support our finding that SCD has a stronger influence and a higher relative weight effect on alpine phenology compared to SWE_m. In addition, the snow melt date and snow depth are often strictly linked (Hejcman et al., 2006). Together with springtime temperatures, the depth of the winter snowpack determines the timing of snowmelt (Richardson et al., 2013). Therefore, the timing and accumulation of snow may have synergistic effects with spring temperature in the determination of the alpine phenology.

Second, we found LOS be equally influenced by SCD and SWE_m across elevations (Figure 5b). In alpine ecosystems, snow may influence LOS through its effect on vegetation greenness (Trujillo et al., 2012). A deeper snowpack raises winter soil temperatures and may increase soil moisture and nutrient availability and lead to higher rates of litter decomposition (Chen et al., 2005; Wahren et al., 2005). In contrast, thin and early melting snow may result in plants being exposed to cold air temperatures that cause frost damage or inhibit rates of development (Wipf et al., 2006). For instance, Hiller et al. (2005) reported that low temperature, saturation of soil with water during snowmelt, and occasional drought may hamper plant activity during the growing season in the alpine tundra. In contrast, deep and late melted snow provides frost protection (Desai et al., 2016; Hu et al., 2010) for the plants until air temperatures are suitable for growth (Richardson et al., 2013). In addition, abundant snow will also result in increased N mineralization, N_2O flux and net nitrification (Williams et al., 1998). These aspects may demonstrate the importance of both SCD and SWE_m for LOS.

4.4. Potential Climate Change Influence on Future Alpine Phenology

According to the latest Climate Change Advisory Body (OcCC) Consortium report (OcCC-Consortium, 2007) on the Swiss Alps, a temperature increase of 2°C in winter and spring, and a precipitation increase by 10% in winter can be expected by 2050. Changes in temperature-precipitation patterns may result in snowpack increases (Beniston, 2012; Saccone et al., 2012) in midwinter above 2,000 m asl (Marty & Meister, 2012; OcCC-Consortium, 2007), where grasslands (i.e., SV and NG) are predominant. In addition, several studies

(Beniston et al., 2003; Keller et al., 2005; Rammig et al., 2010) expect significantly earlier snow meltout dates at these elevations, by as much as a few weeks, until the end of the 21st century. These temperature-precipitation changes could also result in increasing SWE_m but decreasing continuous SCD above 2,000 m asl in the future. Furthermore, variation of timing and accumulation of snow will influence the phenology and growth of plants in alpine regions (Abeli et al., 2011; Julitta et al., 2014; Keller et al., 2005), which will in turn affect the distribution and composition of vegetation (Jonas et al., 2008; Löffler, 2005; Wipf & Rixen, 2010).

Our study showed significant influence of SCD and SWE_m, unlike LSD, on both SOS and LOS (section 3.2). This supports the previous findings that the future variation of snow cover and accumulation, which codetermine the sensitivity of alpine ecosystems to warming (Menzel et al., 2006; Pellerin et al., 2012), may alter alpine vegetation distribution and composition. In addition, the relative importance of each snow metric to land surface phenology may change in the future. At elevations dominated by forest (i.e., CF, MF, and BF), this study found less significant relationships between snow and phenology metrics (Figures 3 and S7–S9). In addition, our study found a smaller SWE_m and a shorter SCD in forest compared to grassland (Figure S2). A warmer climate, however, may result in longer vegetation activity and shorter SCD in temperate deciduous forests (Richardson et al., 2013). In forest ecosystems, soil carbon sequestration rates may be affected by a warmer climate due to changes in snow cover depth (Monson et al., 2006). Soil temperatures are generally lower in snow-free regions than in snow-covered regions (Groffman et al., 2006), and they increase with snow depth (Richardson et al., 2013). Nevertheless, future change and response of forest ecosystems will more likely be driven by other factors than snow, for instance, temperature, solar radiation, and rain.

4.5. Limitation and Outlook

Several studies point out that snow presence in vicinity of green vegetation may result in errors when detecting greenness (Jönsson et al., 2010; Quaife & Lewis, 2010). Consequently, the dynamics of snow cover may impact satellite monitoring of land surface phenology in vegetated regions (Jönsson et al., 2010; White et al., 2009). Moreover, satellite-derived SCD and LSD can be error prone, especially in conditions when snow cover and clouds are spectrally difficult to distinguish (Xie et al., 2017). Uncertainties in SWE estimates arise with snow under critical illumination conditions and snow in forested regions (Thirel et al., 2012).

A number of questions remain and require further research, in particular related to driving factors such as temperature, precipitation, and solar radiation. In addition, a combination of long-term in situ observations and remote sensing of snow and vegetation phenology will be necessary to better investigate the relationships between snow metrics and land surface phenology in future research in the Swiss Alps.

5. Conclusion

This study assessed the impact of snow metrics on the vegetation activity of mountainous ecosystems. We used a novel 250 m satellite-based snow cover and mountainous land surface phenology data set and 1 km modeling-based snowpack accumulation data set of the Swiss Alps (2003–2014). The results show that the variations in SCD, LSD, and SWE_m explained 71.0% of the interannual changes in SOS of 21.5% NV pixels, and 70.0% in LOS of 14.5% NV pixels above 1,500 m asl where snow metrics were not mutually correlated.

Our analysis concluded that (i) SCD was correlated with SWE_m, although both SCD and SWE_m showed no significant correlation with LSD; (ii) mountainous phenology was more sensitive to timing and accumulation of snow above 1,500 m asl than below; (iii) the relationship of mountainous phenology with snow was more pronounced in high-elevational regions such as the WSA and ESA, as well as in alpine vegetation types such as natural grassland and sparsely vegetated areas as compared to other areas; and (iv) SOS was influenced primarily by SCD, secondarily by SWE_m, while LOS showed equal effects from SCD and SWE_m across elevations. In contrast, LSD showed no significant effect on both SOS and LOS across elevation in the Swiss Alps.

The results presented here indicate that alpine ecosystems are significantly sensitive to timing and accumulation of snow variation associated with elevation. Moreover, changes in high-elevation vegetation activity and composition should be expected in response to changes in timing and accumulation of snow. However, along with extreme events and land use practices, other factors such as temperature, precipitation, and soil water and nutrient availability might lead to linear or nonlinear changes in phenology in the regions where snow plays a limited role. Unfortunately, it is difficult to make future predictions based on short-term analyses. Nevertheless, the role of the above factors in the future, combined with possible climate change scenarios in mountainous regions, was beyond the research scope of this study and remains to be investigated.

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